COMPLEXITY AND THE LIMITS OF ECOLOGICAL ENGINEERING

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ABSTRACT. *The present–day concept of complexity is reviewed and discussed with respect to its potential implications on the practice of ecological engineering applied to ecosystems. It is argued that ecological engineers must incorporate concepts arising from complex system studies such as emergence, scaling, self–organization, and unpredictability into their conceptual model of an ecosystem in order to effectively design, manage, or restore such systems. These four concepts are introduced with reference to complex systems in general, and then with specific reference to ecosystems. A discussion of how ecological engineering should be approached in the context of complex system studies is then presented. While the article specifically addresses ecological engineers, the content is also applicable to anyone working in ecosystem restoration and natural resource management.*

Keywords. *Complexity, Complex systems, Ecological engineering, Ecosystem management.*

With the ever–growing pressures on the environment caused by a rising human population and the associated consumption of natural resources, engineers are increasingly required to deal with problems related to environmental management, ecosystem restoration, or the mitigation of human impact on wildlands. The result is that many engineers now find themselves applying engineering principles to ecological systems that, unlike the structures and machinery that constitute the stereotypical domain of an engineer, are made up of living components.

Working with ecosystems was once a task relegated to a small fraction of agricultural and biosystems engineers. Recently, the field has evolved to incorporate a growing number of self–proclaimed "ecological engineers" whose endeavor is: "the design, operation, management, and repair of sustainable living systems, in a manner consistent with ecological principles, for the benefit of both human society and the environment" [ASAE Ecological Engineering Technical Committee definition, based on Mitsch (1996) and Bergen et al. (1997)]. Ecological engineering differs from other branches of engineering in two key ways: (1) it is founded on an underlying ethic in which the preservation of the global ecosystem is acknowledged to be of key importance, and (2) it has ecology as its fundamental science base. An ecological engineer, therefore, works within the constraints of a code of ethics that requires designs that improve human welfare while at the same time protecting and sustaining the natural environment in which we live.

It is argued here that for ecological engineering to be successful as a viable profession, its practitioners must develop a new set of principles and practices that accommodate the variability and unpredictability of living systems. Such principles and practices must be clearly defined and be applied with the same degree of rigor as is seen in any other branch of engineering. An excellent preliminary set of basic conceptual principles with guidelines for ecological engineering was proposed by Bergen et al. (1997) and further elaborated in a later article (Bergen et al., 2001). They are, in brief:

- Design consistent with ecological principles.
- Design for site–specific context.
- Maintain the independence of design functional requirements.
- Design for efficiency in energy and information.
- Acknowledge the values and purposes that motivate design.

These principles build on and incorporate ideas previously proposed by practitioners in the field of ecological engineering (Bergen et al., 2001). While their publication represents a significant step in the right direction, there does not yet exist a generally accepted set of principles that define and establish ecological engineering as an accredited branch of the engineering profession.

The objective here is not to propose new principles, but rather to suggest that those that are developed be based upon a science of ecology in which living systems are viewed as complex systems. In this context, several key aspects of system complexity of relevance to ecological engineers are introduced and briefly described, and the potential implications that these have for engineering practice are discussed. This article is not intended to be an exhaustive review of complexity theory; for this, the reader who desires further information is advised to consult the references cited herein. Instead, the article is intended to incite discussion and debate about how ideas arising from complex system studies can be used and incorporated into ecological engineering practice.

COMPLEX SYSTEM STUDIES

Contemporary complexity theory, the origins of which can be traced back to early cybernetics research (see, for example, Ashby, 1956), is a synthesis of recent developments

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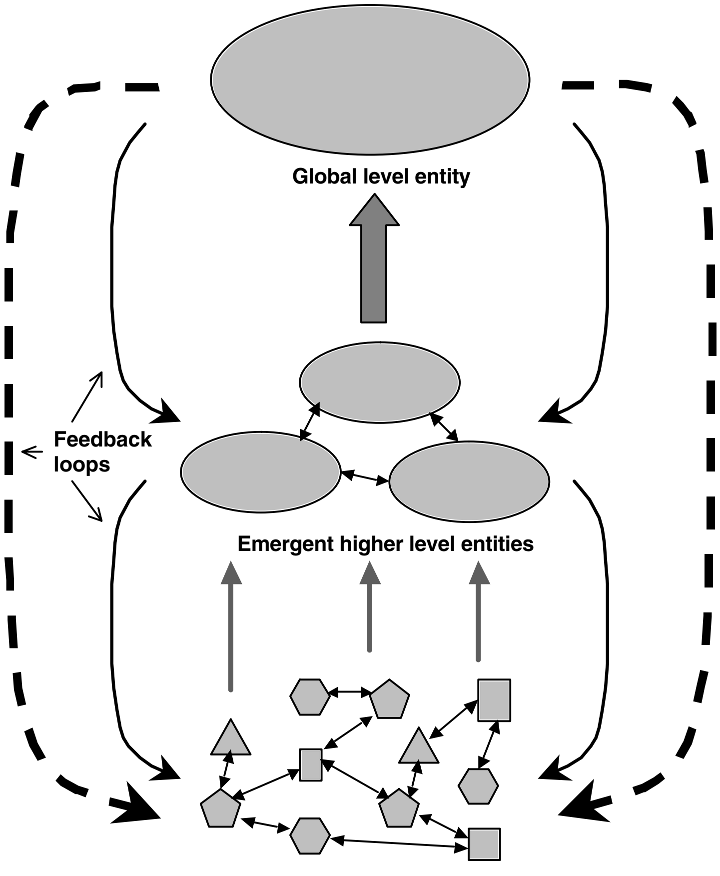

Figure 1. Hierarchy of organizational levels in a complex system. Locally interacting components give rise to emergent, higher–level entities, whose existence, in turn, affects the behavior of the lower–level entities.

in fields such as non–linear physics and modern dynamical systems studies (Heylighen, 1997). It enables the identification, characterization, and comparison of the structure and dynamics of many types of natural and artificial systems, and it is being widely adopted in disciplines ranging from economics and social policy to biology and physics (Waldrop, 1992). Complexity theory differs from other analytical approaches in that it is based on a conceptual model in which entities exist in a hierarchy of interrelated organizational levels (fig. 1). Thus, whereas in conventional approaches systems are described at only one level of organization (e.g., community or nation, but not both simultaneously), complexity theory provides a framework in which the relationships between constructs at different hierarchical levels can be accommodated. In this manner, the conceptual model that serves as the foundation for complexity theory engages a somewhat larger "depth of field" than that of conventional analytical models. This increased depth of field facilitates the study of phenomena such as those caused, for example, by what Hofstadter (1979) has called "strange loops": situations in which the activities of entities interacting at a lower level give rise to higher–level constructs, the existence of which affects the dynamics of the lower–level entities that created them; in Hofstadter's words, a "self–reinforcing 'resonance' between different levels." Through the identification of strange loops and other multi–level structures, the analysis of systems from the perspective of complexity theory makes possible new explanations for a wide variety of phenomena that are not easily explained with analytical methods based on non–hierarchical conceptual models.

Systems whose global dynamics are determined to a large degree by hierarchical relationships such as strange loops are therefore referred to as complex (in contrast to simple systems, whose comportment is usually a linear superposition of component behavior). There are many working definitions of a complex system, the simplest perhaps being that proposed by the editors of *Science* as: "one whose properties are not fully explained by an understanding of its component parts" (Gallagher and Appenzeller, 1999). This can be more formally phrased as "a network of many components whose aggregate behavior is both due to, and gives rise to, multiple–scale structural and dynamical patterns which are not inferable from a system description that spans only a narrow window of resolution" (Parrott and Kok, 2000). Typical examples of complex systems include ecosystems, economies, transportation networks, and neural systems.

A key aspect of the definition given above is the concept of scale, or the "lens" through which a system is observed, since, in a complex system, different components and structures are evident only at different spatial and temporal resolutions. Generally, these "observable regularities" cannot be easily described with a few parameters, or even with a single model. Thus, much of the research pertaining to complex systems is focused on the observation and measurement of a given system's complexity, which is an observer–dependent term that can be most simply defined as a system's degree of intractability, i.e., the amount of information required to describe its observable regularities (Gell–Man, 1994).

FEATURES OF COMPLEX SYSTEMS

Although there are others, the key features of a complex system that are most generally attributed to system complexity, especially in ecosystems, include emergence, self–organization, scaling, and unpredictability.

Emergence

The concept of emergence is used to describe the unexpected, or unforeseeable, appearance of spatial or temporal patterns in the structures and dynamics of a system. More precisely, emergence may be defined as "a process in which a collection of interacting units acquires qualitatively new properties that cannot be reduced to a simple superposition of individual contributions" (Prusinkiewicz, 1994, p. 61). Emergence gives rise to some of the most interesting dynamics in complex systems, including the formation of waves and vortexes, the social ordering of bee colonies, and the development of consciousness in brains (Solé and Goodwin, 2000). Assad and Packard (1992, p. 145) have defined emergence on a relative scale from weakly emergent ("behavior is deducible in hindsight from the specification after observing the behavior") to strongly emergent ("behavior is deducible in theory, but its elucidation is prohibitively difficult") and maximally emergent ("behavior is impossible to deduce from the specification"). They hypothesized that strong or maximal emergence seems to be a typical characteristic of the dynamics of most living systems.

The concept, in fact the very existence, of the phenomenon of emergence in ecological systems has been the subject of much debate. There are those who claim that absolute emergence doesn't exist and that emergence is always a relative term that is indicative of our scope of knowledge about a system at a given time. This argument is founded on a mechanistic worldview in which is it believed that the entire comportment of a system is predictable, given a sufficiently detailed description of that system. Edson et al. (1981), for example, argued that emergent properties in ecosystems are merely the result of aggregate interactions for which there is no known composition function (in contrast to properties acquired as the result of additive functions) and are therefore not qualitatively different and not deserving of special attention. While Edson et al. (1981, p. 394) proposed that "there can be no claims of absolute emergence (inherent unpredictability)," automata theory has proved that some behaviors cannot be predicted any faster than by the system in which they occur (Langton, 1989). In such cases there is no model, short of the system itself, that would be capable of predicting all aspects of that system's comportment. Behaviors that are unpredictable in this sense are what most researchers would call emergent.

Self–Organization

Emergence is the product of self–organization: the generation of spatio–temporal order under non–equilibrium conditions in the absence of any macroscopic description of that order (Shrödinger, 1944; Haken, 1977; Gell–Man, 1994). The concept of hierarchy is key to the description of self–organization, which, in order to be non–trivial in nature, requires that events at one scale set the stage for the occurrence of events at another scale (O'Brien and Weissman, 1992). Self–organization is, therefore, the process by which the combined, apparently disordered, activities of a large number of locally interacting entities cause sustained, substantially ordered structure and comportment at the system, or global, level. Usually, self–organization is achieved and maintained by a dynamic system so long as there is a continual flow of some resource (e.g., energy, matter, or information) across the system boundary, thereby resulting in a net entropy export.

The concept of self–organization is becoming increasingly prevalent in ecology, where it is used to explain a number of phenomena in ecosystems. In these systems, the seemingly random, or erratic, behavior of individual organisms, in conjunction with random environmental influences, has been shown to lead to persistent, self–organized structures and dynamics at the population scale (e.g., dispersal or flocking patterns, quasi–equilibrium, resilience or persistence of species in ecological communities), which, in turn, affect the behavior of the individuals in the populations (Levin, 2000). Commenting on this, Fahse et al. (1998, p.849) concluded that: "It may turn out in the future that the notion of ecological systems as being self–organized leads to a deeper understanding of ecological principles than the notion of self–regulation and negative feedback, which are cybernetic notions and as such omit any reference to the basic unit of ecological systems, the individuals." In addition, several authors have proposed that the self–organization of ecosystems is an essential component of ecological integrity (Kutsch et al., 2001; Schneider and Kay, 1994). A related concept is that of autopoiesis (Maturana and Varela, 1980): the ability of a system to be self–regenerating, or self–forming, such that global–level structures and components remain persistent over time, even as lower–level components are replaced. Ecological systems demonstrate this capacity in many ways, an example being the maintenance of overall food web connectivity and trophic structure over periods of time that exceed the lifespan of the individual organisms contributing to this structure.

Scaling

Unlike a fractal (Mandelbrot, 1982), which is self–similar across many scales, a complex system is often dissimilar at different scales (although fractal structures may still be present). This is the concept of scaling: the idea that for each given level of resolution at which a system is observed, a different model can be written to describe the features that are discernible at that scale (Meyer, 1997). This concept is a key part of quantitative landscape analysis and ecological hierarchy theory (Turner et al., 1991), and it contributes to the many problems associated with the interpretation and analysis of remotely sensed data (Marceau, 1999). From an information–theoretic perspective, it can be argued that a complex system exploits the capacity to process information by differentiating its processing ability across scales through the use of an organizational structure that is markedly dissimilar at different resolutions. In this regard, Wolpert and Macready (1997) have hypothesized that in nature there is a selective advantage to maximizing the amount of information processed by a system in any given volume of space, since a system that processed information similarly on every scale would not be making efficient use of its available resources. Similarly, Holling (1996) has proposed that natural mechanisms of management and self–regulation in ecosystems maintain these systems on the "edge of instability" in order to maximize information processing, and, therefore, evolutionary opportunity.

Unpredictability

The interconnected, hierarchical levels of organization in a complex system give rise to a class of system dynamics that is not easily characterized with standard analytical techniques and which tends to fall somewhere between the completely ordered (e.g., simple periodic cycling) and the totally disordered (e.g., uncorrelated random noise). This type of dynamics has been coined the "edge of chaos" (Langton, 1990).

The concept that complex systems, and especially ecosystems, may have organizational structures that keep them in non–equilibrium, yet persistent states at "the edge of chaos," may be explained by self–organized criticality theory, as promulgated by Bak and colleagues (Bak, 1996; Bak et al., 1988; Bak and Chen, 1991; Gell–Mann, 1994). This theory states that some large, many–body systems "naturally evolve to a critical state in which a minor event starts a chain reaction that can affect any number of elements in the system" (Bak and Chen, 1991, p. 46). It has been used to explain the spatial and temporal distributions of a wide range of natural events, such as earthquakes, forest canopy gaps, and extinctions (e.g., Solé and Manrubia, 1995). An equally important implication is that "composite systems never reach equilibrium but instead evolve from one meta–stable state to the next" (Bak and Chen, 1991, p. 46). (It is implied here that the system under discussion is open, and subject to continuous inputs.) In paleobiology, this type of dynamics has been termed "punctuated equilibrium" (Gould and Eldridge, 1977), since species have been observed to undergo gradual evolutionary change, punctuated by rapid, radical changes at certain times in the history of Earth. Thus, despite the presence of strong evolutionary and environmental pressures, there are long periods of relatively stable species records. Similarly, the tendency of ecosystems to remain globally stable despite underlying change has been noted by many researchers (Holland, 1995) and is, of course, typical of any autopoietic system. It is precisely this type of dynamics that enables the prediction of long–term trends in natural systems, but which prevents precise forecasting at finer resolutions.

Lastly, it should be noted that non–trivial complex behavior arises in systems that have a high degree of heterogeneity and diversity among their constituent components (Levin, 1999). A complex system is not simply one made up of many parts; it is the differentiation between the parts that gives rise to all the types of interesting and varied behavior that we classify as "complex."

BRINGING TOGETHER COMPLEXITY AND ECOLOGICAL ENGINEERING

There are a number of key implications of complexity theory for ecological engineers as well as others working on, for example, ecosystem management and restoration projects. Some of these, such as the notion of scale (Odum, 1996) and the need to harness a system's ability to "self–design" (Mitsch, 1998) (a notion somewhat akin to self–organization) are already important tenets in the ecological engineering literature. Others, such as the inherent long–term instability and lack of predictability of ecological systems, continue to defy certain engineering projects.

The first, and perhaps most fundamental, lesson to be learned is to accept change: to recognize that ecosystems are dynamic systems in a perpetual state of flux. This is an idea that has been underscored in many recent texts on ecosystem management and has led to theories of adaptive management to compensate for the associated uncertainty (Walters, 1986). Accepting the idea of constant change requires a new engineering perspective, and an acknowledgment that the unexpected will occur, especially as the result of emergence. In ecosystem management, the challenge becomes one of deciding if an unexpected event or re–structuring of the system is indicative of the system's eventual demise, or if this is simply a natural part of the system's on–going evolution.

Due to our limited predictive abilities, living systems cannot be designed with absolute certainty. When dealing with complex dynamics, it is likely that the best prediction that can be made is one that delineates a window of probable future system states. In ecosystem management, therefore, this means that the long–term behavior of a system cannot be predicted precisely, and that the outcome of a management decision is therefore unknown. In restoration projects, for example, it is often exceedingly difficult to guarantee the success of a reintroduced species. Community dynamics may be ruled by lower–level interactions that give rise to unpredictable (emergent) results, causing a carefully reintroduced species to be out–competed by another exotic or hardy transition species (Levin, 1999). Due to the complex web of inter–species interactions that occur at a local (i.e., organism to organism) level, it is often almost impossible to predict a restored system's final community structure with any degree of certainty.

Thus, rather than futilely seeking better predictive tools, the ecological engineer should instead strive to understand the underlying organizational forces in a system and work to guide or bolster these, allowing the system to manage itself within a viable window. This is the notion of self–design: the idea that an assemblage of living components will optimize its organization by selecting for those parts that together are best adapted to the prevalent environmental conditions. The engineering strategy thus becomes one of putting the right set of conditions in place so as to encourage the self–design of a system. This strategy has been successfully implemented in numerous projects, notably the design of "living machines" (Todd and Todd, 1994).

Unlike simpler systems, ecosystems do not have single equilibria states that they can be controlled to remain near. Instead, a given ecosystem may have multiple stable states, and moving between these states may play an important role in the maintenance of diversity and a flexible structure (Levin, 1999; Holling, 1996). Management policies that apply fixed rules to ensure a sustained yield or carrying capacity inevitably lead to increased brittleness in system structure, causing the system to break down or collapse in the face of a disturbance that previously could have been absorbed (Gunderson et al., 1995; Holling, 1996; Schneider and Kay, 1994).

Learning to engineer ecosystems therefore requires an understanding and acceptance of the constraints imposed on their design by their dynamic, ever–changing nature. Unlike most engineered systems, a resilient ecosystem will naturally adapt itself to changing external inputs. A good design will incorporate this resiliency, while at the same time introducing elements that guide the system such that its global–level dynamics continue to meet the desired functional requirements. As Holling (1996) has argued, engineering ecosystems requires an approach that maintains the system's "ecological resiliency," i.e., the amount of disturbance that can be sustained by a system before a marked change in system structure or function occurs. This necessitates, minimally, maintenance of diversity and cross–scale functional redundancy in any ecosystem design.

Peterson et al. (1998, p. 16) have proposed that "ecological resilience is generated by diverse, but overlapping, function within a scale and by apparently redundant species that operate at different scales." An awareness of the concept of scale and the idea that there are distinct and often equally important features at different scales necessitates a broad approach to assessing the health of an ecosystem in which measures are taken at a variety of spatial and temporal resolutions. Likewise, in terms of ecosystem maintenance or restoration, a manager or engineer needs to take precautions to regularly assess and maintain the integrity of features at all scales. If not, the system may not have the resiliency and robustness required for long–term persistence. Lastly, the role that heterogeneity and diversity plays in ecological dynamics should not be ignored; a goal of any ecological engineering project should be to introduce heterogeneity and set in place the appropriate mechanisms for the maintenance of this heterogeneity.

SUMMARY

Persistence of species, food web stability, quasi–equilibrium at one of several stable states, and most other aspects of ecosystem health and integrity are maintained via a number of phenomena, such as strange–loops, self–organization, and emergence, that are not fully understood. It is known, however, that these phenomena are universally characteristic of ecosystems and living systems in general. Thus, before a complete set of principles and guidelines for the engineering of living systems can be devised, the conditions that give rise to these phenomena need to be elucidated.

Engineers have excelled at solving design problems by dividing systems up into easily manageable sub–components that are later assembled to produce a final product. For all of the reasons presented above, complexity theory would suggest that, for natural systems at least, this cannot be done. Ecological engineers would be wise to bear in mind Cohen and Tilman's (1996) words of caution, with reference to experience gained from Biosphere 2 closure experiments: "At present there is no demonstrated alternative to maintaining the viability of Earth. No one yet knows how to engineer systems that provide humans with the life–supporting systems that natural ecosystems produce for free. Dismembering the major biomes into small pieces, a consequence of widespread human activities, must be regarded with caution. Despite its mysteries and hazards, Earth remains the only known home that can sustain life."

If complexity can be defined, in engineering terms, as "the measure of uncertainty in achieving a design that meets stated functional requirements" (Suh, 1999), then living systems such as ecosystems are perhaps the most complex systems of all. It may be that an ecosystem cannot be precisely designed at all and must instead be synthesized or evolved, or created with a combination of approaches (Langton, 1989; Bonabeau and Theraulaz, 1994). Minimally, recent research in complex system studies would suggest that ecological engineering must be performed with an increased awareness of the conditions that give rise to the complex patterns and structures in these systems, which until recently have been treated in a much simpler manner, or completely overlooked.

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